VISION EXPERIMENT II ON WHITE LIGHT CHROMATICITY FOR LIGHTING

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Abstract

In response to a published discussion (Wei & Houser, 2015) on the 2013 NIST experiment on white light chromaticity for lighting (Ohno & Fein, 2014), the second experiment was conducted at NIST to determine the white light chromaticity perceived most natural in a simulated interior room environment using the NIST Spectrally Tunable Lighting Facility. The 2015 experiment was conducted with 21 subjects, for shift of Duv (chromaticity shifts above and below the Planckian locus), using the same procedures as the 2013 experiment but minimizing the changes in gamut area in each pair of lights compared so that only the effects of chromaticity would be evaluated. The results showed that the lights with $D_{uv} \approx -0.015$, nearly the same as the results in 2013, appeared the most natural at all correlated color temperatures.

Keywords: colour rendering, white light, chromaticity, light source, Planckian locus, preference

1 Introduction

Traditionally the white chromaticity points of light sources for general lighting have been designed to be around the Planckian locus, as specified by the standards for fluorescent lamps (e.g., IEC, 1997, ANSI, 2001) as well as by the recent standard for solid state lighting products (ANSI, 2015). These specifications assumed that Planckian radiation for lower correlated color temperature (CCT) and daylight for higher CCT ranges would be natural white light, but these were not based on visual experimental data. In this paper, chromaticity shifts away from the Planckian locus (yellowish/pinkish shift) is expressed by Duv (Symbol: D_{uv}), which is defined as the shortest distance from the chromaticity of the light to the Planckian locus on the CIE (u', $2/3v'$) coordinates, with plus sign for above and minus sign below the Planckian locus, as defined by (ANSI, 2015) and also described in a recent article (Ohno, 2013).

A recent study on a vision experiment (Rea & Freyssinier, 2013) reported that perceived neutral white points are $D_{uv} \approx -0.01$ at 2700 K to 3500 K, $D_{uv} \approx 0.00$ at 4000 K, and $D_{uv} \approx 0.005$ at 6500 K (though the report did not use Duv). This experiment was done with a lighting booth with white inner walls and no objects inside. Another experimental study (Dikel et al, 2014) showed that subjects viewing an office miniature set preferred white light illumination of Duv around -0.014 on average. In 2013, vision experiments were conducted at NIST for white points perceived most natural in a simulated real-size interior room environment using the NIST Spectrally Tunable Lighting Facility (STLF) (Miller et al 2009), with 18 subjects. The results showed that the lights with $D_{uv} \approx -0.015$ on the average, much below the Planckian locus, appeared most natural (Ohno and Fein, 2014). This experiment used broadband spectra, and the gamut area for saturated object colors naturally increased as the Duv shifted to the negative direction.

Following this research, a discussion (Wei & Houser, 2015) was published that the results of the NIST 2013 experiment might have been caused by the changes of gamut area and other color quality characteristics, rather than change of chromaticity. It was considered to be an important point to clarify. To address this question, another series of vision experiment was conducted at NIST in 2015 so that the effect of only chromaticity could be evaluated, with other effects such as color gamut or chroma saturation minimized.

2 Method

The experiment was conducted using the same facility (NIST STLF) and the same procedures as those used in 2013, with only light spectra modified. See (Ohno & Fein, 2014) and (Miller et al 2009) for the details of the NIST STLF.

Fig. 1 shows the curves of Color Rendering Index (CRI) R_a, Color Quality Scale (CQS) Q_a, Q_f, and Q_g (Davis & Ohno, 2010), for the spectra used in the NIST 2013 experiment. Q_g is the relative gamut area of the 15 test samples of CQS on (a*, b*) coordinates of CIELAB color space. Fig. 2 shows a few examples of the gamut area plots at 3500 K. As shown in these figures, the relative gamut area increases as the Duv changes in the negative direction, which is the reason for the discussion by Wei and Houser (2015). Increase of the gamut area at negative Duv is inevitable because the green region of the spectra must decrease to bring the chromaticity below the Planckian locus, which in turn increases the luminance of colored objects (compared to that with the reference illuminant at the same illuminance). This effect cannot be removed over the large range of Duv (-0.03 to 0.02). However, the 2013 experiment consisted of a number of comparisons of light pairs of small Duv differences, and it was possible with NIST STLF to adjust the light pairs so that the gamut area and chroma differences in each pair were made nearly equal.

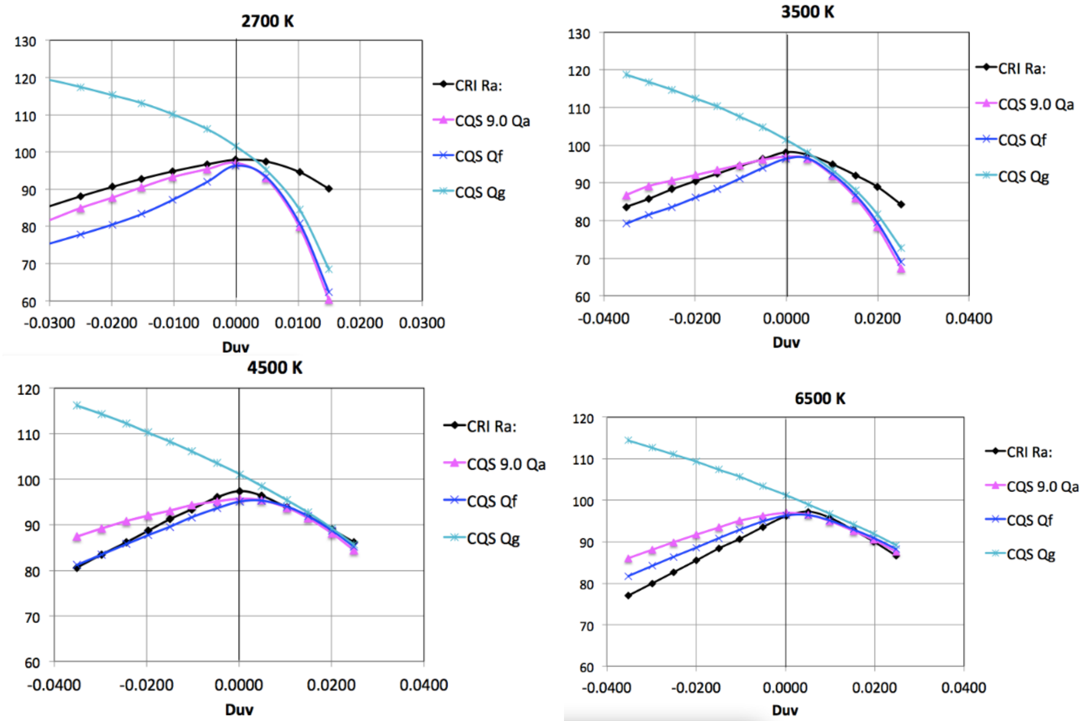

Figure 1 – CRI and CQS color quality values of the lights used in the 2013 experiment.

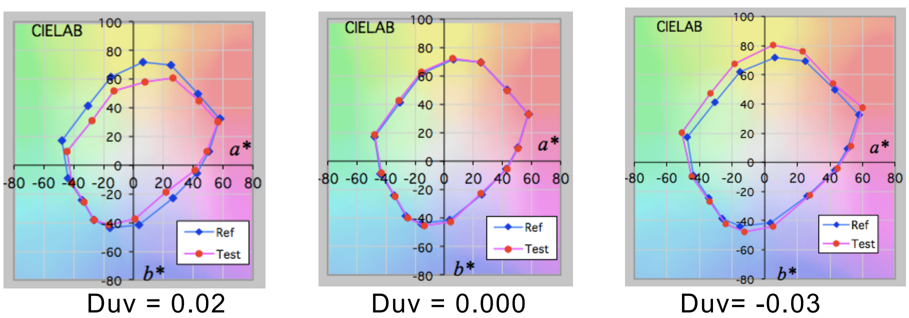

Figure 2 – Gamut area plots of the CQS 15 samples of the lights at 3500 K used in the 2013 experiment. The blue curve is for the reference illuminant (Planckian) and the red curve is for the test light source.

For the 2015 experiment, the broadband spectra, similar to those used in 2013, were first prepared for each Duv point, and they were slightly modified and adjusted so that the gamut area Q_g and the chroma difference ΔC^*_{ab} for the red and green CQS samples would be as equal as possible in each pair of light. Figure 3 shows the plots of Q_g, and Figure 4 shows the chroma difference ΔC^*_{ab} of the red and green test samples of CQS (between the test light and the reference illuminant). The thin solid lines in Figs. 3 and 4 are the same plots of the 2013 experiment data. The intention in 2015 experiment was to remove the slopes and make them as flat as possible between the lights in each pair. As it is difficult to make both of these completely flat, a higher priority was placed in minimizing the chroma differences in the red and green test samples, as these colors are most critical in perception of color quality.

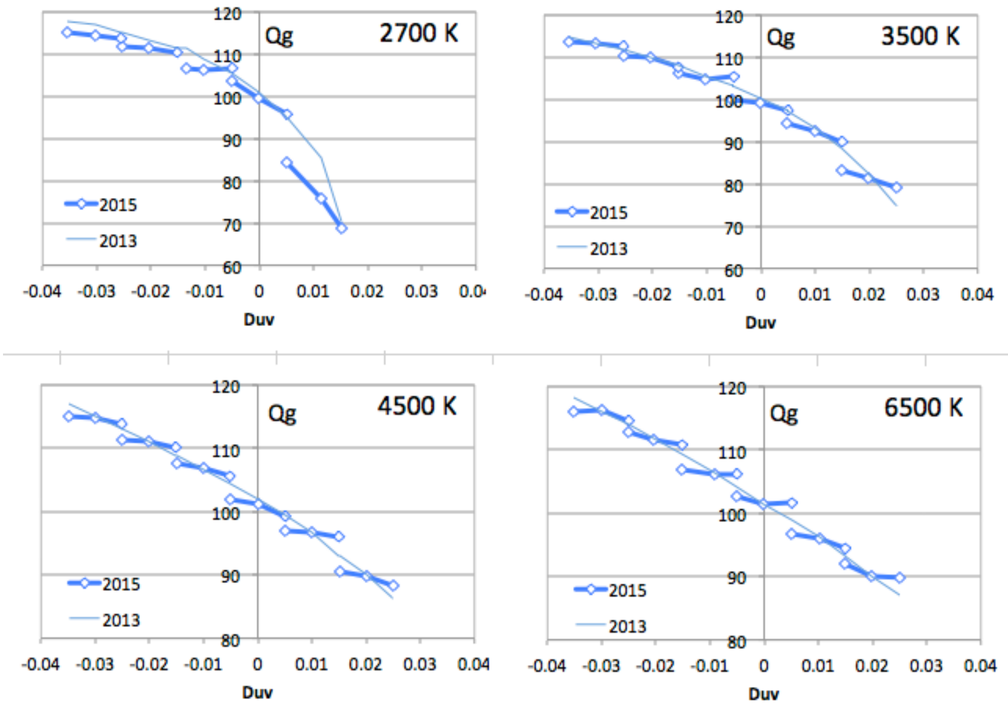

Figure 3 – Plots of the relative gamut area Q_g in the 2015 experiment.

Thus, the remaining differences in the gamut area (Fig. 3) are mostly in the yellow-blue direction, which is much less distinctive in perception of color quality. For example, the average differences in Q_g between two lights in each pair for the six Duv conditions at 4500 K was reduced from ΔC^*_{ab} = 5.1 in 2013 to ΔC^*_{ab} = 1.5 in 2015. The average chroma differences ΔC^*_{ab} for red and green samples between the lights in each pair were reduced from 1.4 (red) and 2.2 (green) in 2013 to 0.3 (for red and green) in 2015, at 4500 K.

The resulting spectra of the lights used in the 2015 experiments are shown in Fig. 5. Each curve corresponds to each point on the graphs in Fig. 3 or Fig. 4.

21 subjects having normal color vision from 19 to 68 years of age participated in the experiment. The subjects were the summer students and employees at NIST, who were not experts on color or lighting.

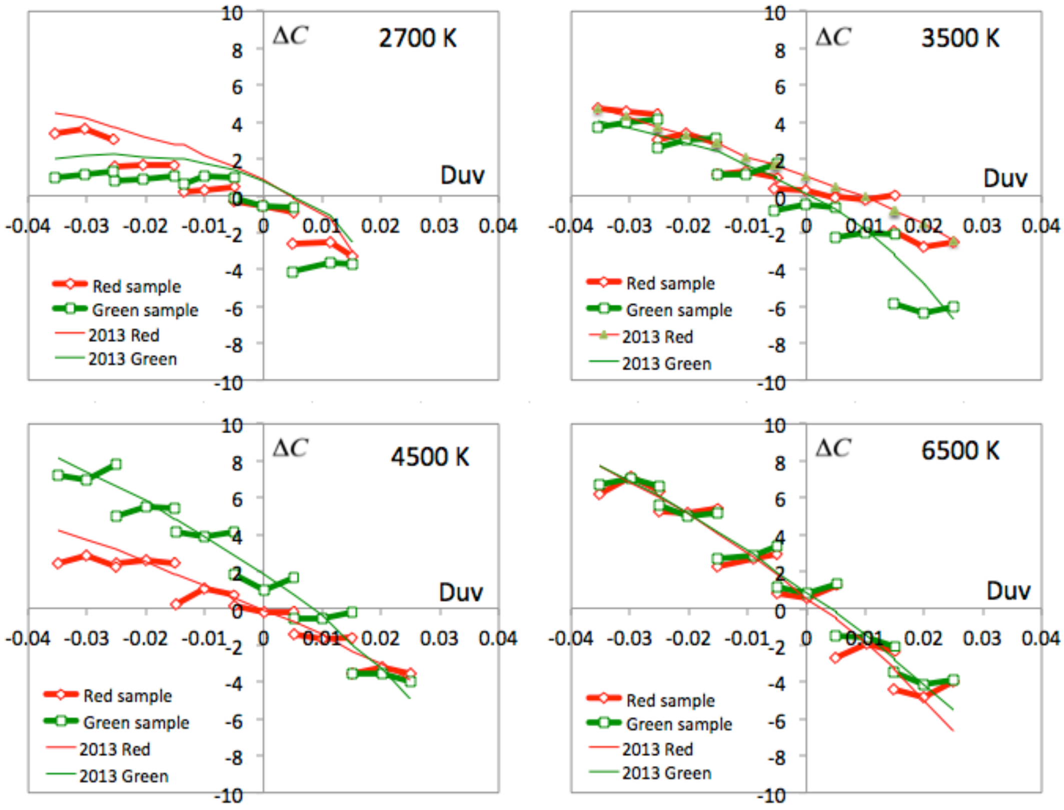

Figure 4 – Plots of the chroma differences ΔC^{*}_{ab} of the red and green test samples of CQS in the 2015 experiment.

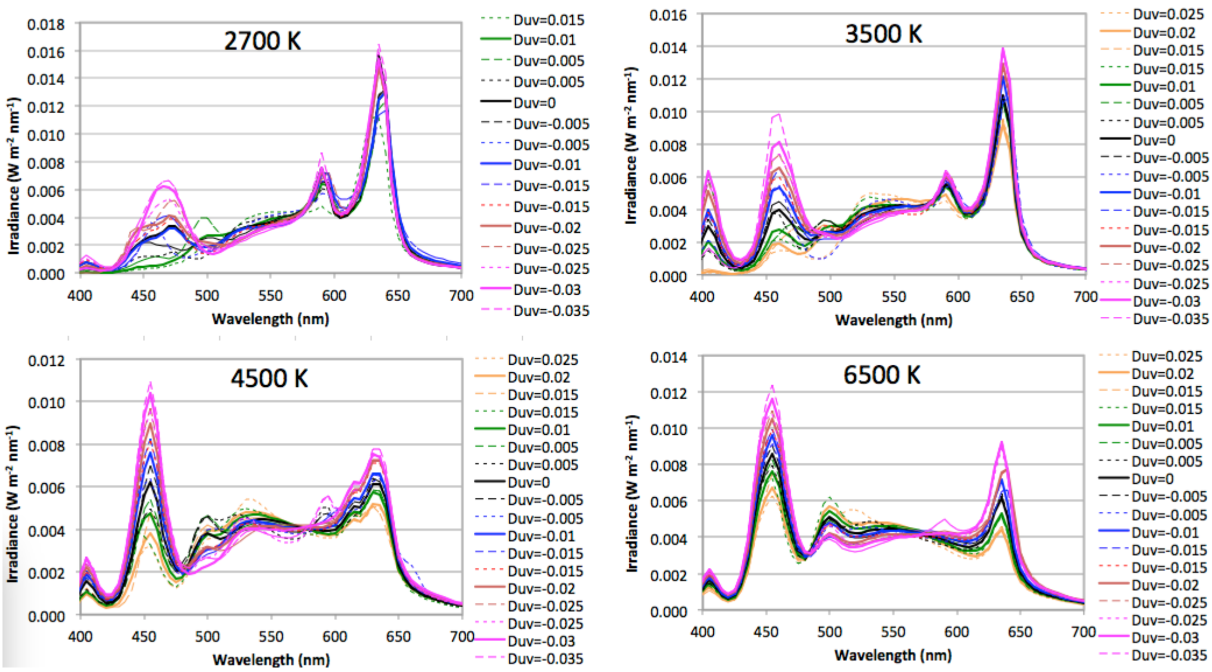

Figure 5 – Spectra of the lights used in the 2015 experiment.

3 Experimental Procedures

The experiments were conducted generally at six different Duv levels (0.02, 0.01, 0, -0.01, -0.02, -0.03) and at four CCTs (2700 K, 3500 K, 4500 K, 6500 K) plus 2200 K, at the illuminance level of 300 lx. These experimental points are depicted in Fig. 6 (black circles). The highest Duv point at 2200 K had to be Duv=0, and for 2700 K, Duv=0.01, because further points would be too close to the spectrum locus and nearly monochromatic. 2200 K was added in this experiment because the CCT categories of 2500 K and 2200 K have been added in the latest version of the ANSI specification (ANSI, 2015) and data at such very low CCTs were desired. However, this was decided at a later stage, this condition was run separate from the other four CCTs, using only six subjects, and no adjustment was made for gamut and chroma saturation (it was very difficult), thus the results for 2200 K was to connect to the 2013 results. The 2200 K experiment was done with 2700 K (2013 setting) again to verify the consistency with the 2013 experiment.

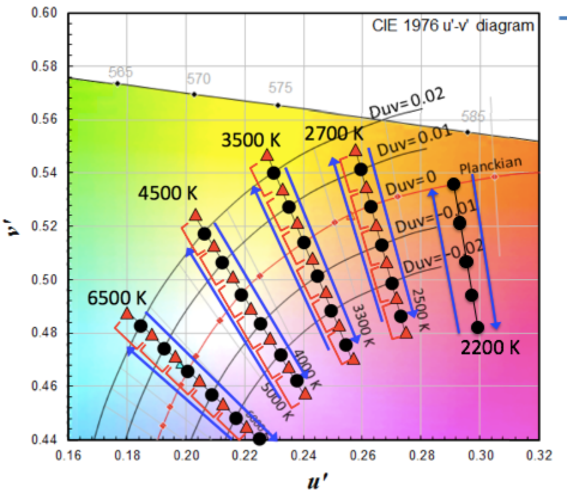

Figure 6 – The chromticity points for the experiment (black circules) and pairs of light for visual comparison (red triangules)

Figure 7 shows the room settings of the NIST STLF. The subject sat on a couch placed at the open side of the cubicle so that he/she viewed the entire room, and was completely immersed in the lighting environment, and his/her full view was adapted to the illumination. For the subjects to be able to judge naturalness of light, common real objects in daily life were placed on the table. They were two dishes of real fruits and vegetables (red apple, yellowish apple, orange, green pepper, lettuce, tomato, banana, strawberries, and grapes). These were the same set of objects as in the 2013 experiment. The fruits and vegetables were replaced at a few days' intervals to keep them fresh. There was a mirror in front of the subject, and he/she could look at their face skin tone in the mirror, as well as their hands skin tone. Along the wall of the cubicle, there was a bookshelf with some books, artificial flowers, and two paintings hung on the side walls. The subjects were asked to make overall judgement of viewing the whole room, fruits and vegetables, and their skin tone.

Figure 7 – The experimental settings of STLF – the room setting (left) and fruits and vegetables on the table (right).

The experimental run was made in the order from high Duv to low Duv (forward direction) and low Duv to high Duv (backward direction) at each CCT condition. The subject was adapted to the light for 5 min at the first Duv point in a CCT (either end of the Duv points) and adapted for 1 min at each subsequent Duv point. See (Ohno & Fein 2014) explaining this adaptation time. After adaptation at each Duv point, a pair of lights (red triangles in Fig. 6), slightly above and below (± 0.005) the adaptation point Duv (black circles in Fig. 6), were presented alternately, and subject chose which light looked "more natural". When starting from D_{uv}= 0.02, for example, a subject typically chose the light with lower Duv shift (toward Planckian) in the pair, which indicates that D_{uv}= 0.02 was too yellowish. At D_{uv}= -0.03, the subject typically chose light with higher Duv shift (toward Planckian), which means D_{uv}= -0.03 was too pinkish. As these comparisons were made from the high Duv end to the low Duv end, or vice versa, subject's response changes over at some point of Duv, and this crossover point of Duv is considered as the most natural point. The crossover point was determined at each run for each subject at each CCT condition. The results for the forward and the backward direction were averaged for each subject and each CCT to remove any effects of imperfect chromatic adaptation or sequential effect. In 2013, the whole experiment depicted in Fig.4 repeated, but in 2015 it was not repeated due to the time limitation. The reproducibility of whole experiment in 2013 was checked that the results of repeated sessions were very consistent, and it was concluded that one session was sufficient.

The experiments were conducted in June to August 2015. Each run for six Duv points for one CCT took 12 to 15 minutes, so about 1 hour for four CCTs, and total about 2 hours for each subject. The order of CCT and the order of forward/backward was randomly set, and the same order was used for all subjects.

The chromaticities of these points were initially adjusted to be within ±0.0003 from the intended chromaticity, and were maintained within ±0.0006 (relative to Duv measured at 0.000) throughout the experiment. The illuminance of all lights were set to 300 lx ± 1 %. The CCT, Duv, and illuminance was monitored before each experiment with each subject to verify that the colorimetric values are stable within the variations as above.

The color quantities of the lights were measured on the center of the table in the cubicle, using an array type spectroradiometer with a small integrating sphere input for cosine response, calibrated with a NIST spectral irradiance standard scale (NIST, 2011). The spectroradiometer measured spectra and illuminance on the table from the 2π solid angle including light from the entire room including reflections from the walls and other objects as well as from the light source itself. The estimated expanded uncertainties (k=2) of measurements varied depending on spectra, but in all cases, they were within 0.0012 in u', 0.0011 in v', 0.0009 in Duv, 24 K in CCT at 2700 K and 92 K at 6500 K. The expanded uncertainty in the relative chromaticity measurement between each pair of light was 0.0002 in u' and v', which is the typical repeatability of the instrument. The expanded uncertainty of illuminance of the spectroradiometer is estimated to be 3 % (k=2) for directional incident light, and its uncertainty for relative measurement was 0.1 %, which is the typical repeatability of the instrument. Also, when the spectrum is changed on STLF, the spectrum and color are switched instantly and stable immediately so that sequential comparison of lights is possible.

The spatial uniformity of color and illuminance in the room was evaluated using the broadband spectra shown in Fig. 5 at Duv=0 setting at all four CCTs. Figure 8 shows the layout of the STLF room and the 28 points measured on the table, floor, and the walls including two positions on the mirror. Measurements were made with a tristimulus colorimeter for chromaticity and illuminance. The uniformity of chromaticity over the table top at all CCTs was within ±0.0013 in (*u’, v’*) and within ±0.0002 in Duv. The chromaticity of all 28 points at all CCTs were within 0.0044 in (*u’, v’*) and within ±0.0010 in Duv from the average chromaticity on the table. The uniformity of illuminance on the table was within ±13 %, on the floor ±16 %, and on the walls ± 15 %. The absolute illuminance on the floor was about 40 % lower, and about 60 % lower on the wall (vertical illuminance) than the average illuminance on the table.

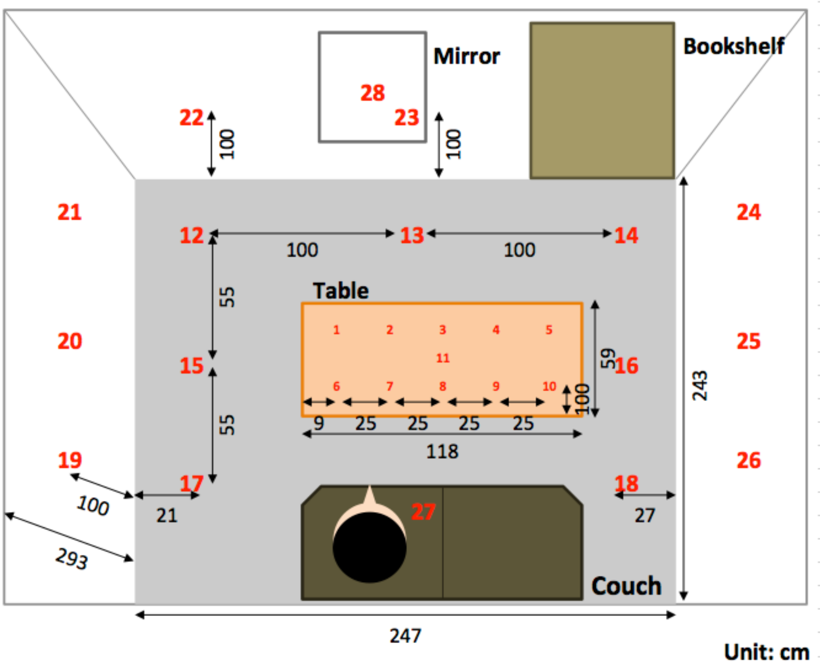

Figure 8 – STLF room layout and the points for uniformity measurements. The red fonts show measurement points.

4 Results

The data analysis was similar to that used in the 2013 experiment. See (Ohno & Fein 2014) for the details. Figure 9 shows the results for the crossover points determined from the 2015 experiment for each subject. Each line in the figure is for each subject. Several straight lines around -0.03 are all at D_{uv}=-0.03 and actually overlapped with each other but lines are shown separately to indicate that there are several lines. Since -0.03 was the lowest Duv used this time, these subjects may have preferred even lower Duv lights.

The results for 2200 K are also included in this figure. Note that 2200 K results are only with six subjects, and the lines from 2200 K are connected to results at 2700 K, which was run at the same time with 2200 K. These six 2700 K points, as well as 2200 K lights, were not adjusted for gamut area and chroma saturation (as explained in section 3) and are different from other 2700 K results where gamut and chroma were adjusted.

The average of all subjects is plotted in the thick red line in Fig. 9. The average results of the 2015 experiment, together with the 2013 experiment, are shown in Fig. 10. The error bars are the standard deviations of the averages of all subjects. Table 1 shows these results numerically. Considering the standard deviations, the average results of the experiments in 2015 and 2013 are practically the same. It was also shown that preference for 2200 K is similar to other CCTs, possibly with larger shifts, but this result is less reliable due to fewer number of subjects.

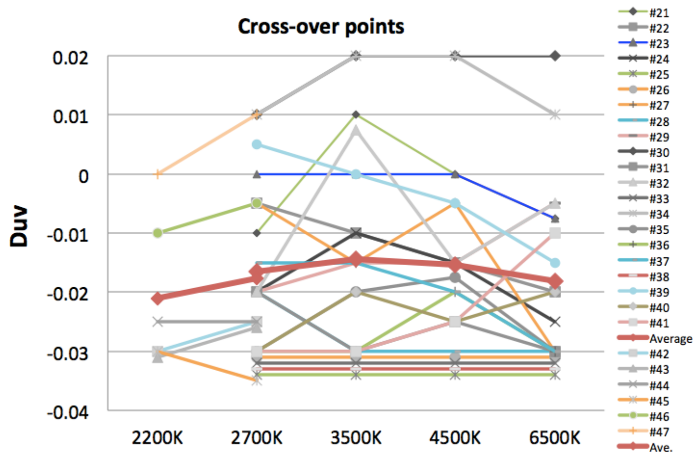

Figure 9 – The results of experiment (crossover Duv points) of individual subject.

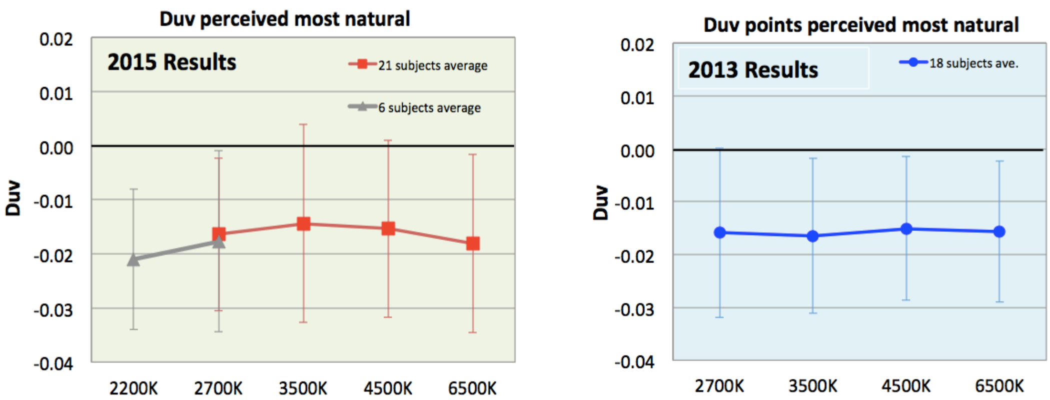

Figure 10 – The average results of the 2015 and the 2013 experiments

Table 1 – Average results of 2015 and 2013 – Duv values at 50 % crossover points and standard deviations.

	2015 Experiment		2013 Experiment	
CCT	Duv at 50 % crossover average	Standard deviation	Duv at 50 % crossover average	Standard deviation
2200 K*	-0.021	0.013		
2700 K	-0.016	0.014	-0.016	0.016
3500 K	-0.014	0.018	-0.017	0.015
4500 K	-0.015	0.016	-0.016	0.014
6500 K	-0.018	0.016	-0.016	0.013

* 2200 K is from six subjects. Gamut area and chroma not adjusted.

The results below are broken down into different conditions and different subject groups, though the number of subjects may not be sufficient for such analyses. Figure 11 shows the results.

There are slight differences between forward and backward direction, which indicates that the adaptation time may not have been sufficient or there may have been some time sequential effects, but the differences are not significant. The differences in sex groups and age groups are also shown but it is uncertain whether these distinctions are significant due to insufficient number of subjects.

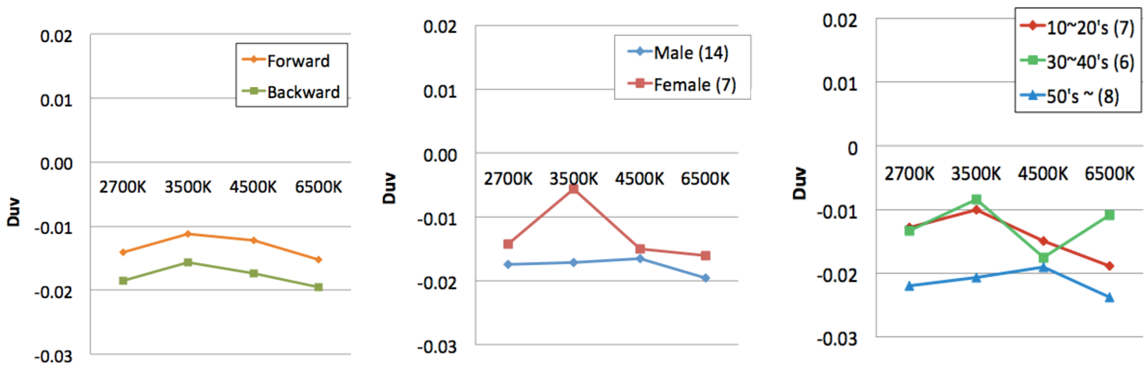

Figure 11 – Break down results for forward/backward, gender, and age groups.

In addition to the results presented above, subjects were also asked whether each presented light after adaptation was acceptable or not, before comparing the light pair. Figure 11 shows the results. All the curves make their bottom at around Duv -0.01 to -0.02, which is consistent with the results of the preferred crossover points reported above. Also, these data show that positive Duv at low CCTs (2700 K and 2200) are clearly disliked by many subjects, while this judgement is less sensitive at higher CCTs.

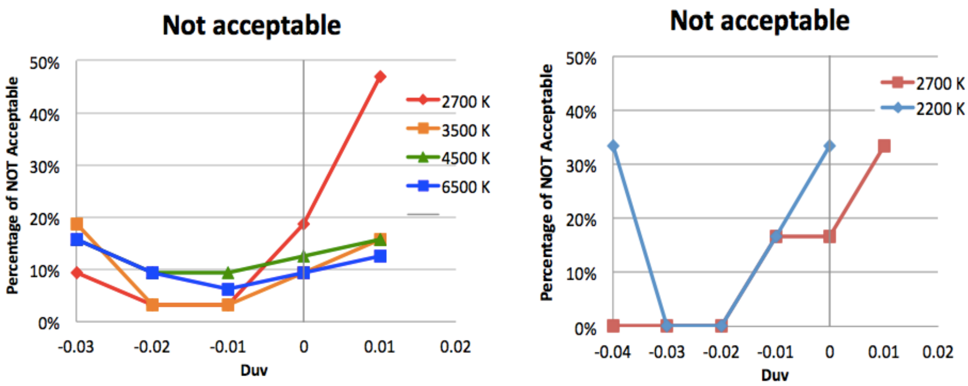

Figure 11 – The percentage of subjects' response of "Not acceptable" for the light presented, after adaptation.

5 Conclusions

The experiments conducted in 2015 clarified that there were no notable effects of changes in gamut area or chroma saturation in the results of the NIST 2013 experiments. It is considered that the preference for negative Duv is mainly due to the effects of light chromaticity, though the increase of gamut area may also be contributing. The two experiments at NIST verified that there is a general preference to the negative Duv lights for typical interior room environment and that the most preferred white light chromaticity, after sufficient chromatic adaptation, was found to be around Duv -0.015 and is consistent over all CCT ranges from 2200 K to 6500 K. This preference, however, may be different for different applications. Also, these results are for the condition when subjects are fully adapted to each Duv point. A shift of -0.015 in Duv may be significant under the transient conditions when the occupants move from one space under such Duv to other spaces or vice versa. Field studies are desired on the preferred Duv levels in various real applications.

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